FURTHER NOTES ON METEOR CRATER, ARIZONA.

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I present this as a supplement to my paper, entitled "Coon Mountain and Its Crater," published in the PROCEEDINGS of The Academy of Natural Sciences of Philadelphia in December, 1905, and to my more comprehensive and necessarily more accurate paper (owing to the amount of exploration work which has been done), read before the National Academy of Sciences at its autumn meeting at Princeton University, November 16, 1909, with a few additional and apparently conclusive arguments with regard to the correctness of the impact theory of origin of what is now known as the Meteor Crater of Arizona.

One of the most significant minor facts in connection with this remarkable crater is the discovery by those who have conducted the extensive exploratory work there of quite large quantities of quartz glass, which is undoubtedly fused sandstone and has been so described by Merrill.[1] An examination of the specimens now on exhibition at the American Museum of Natural History, New York, will immediately convince the most skeptical that this is nothing but fused sandstone.

It does not appear that those who have written on the interesting subject of the origin of this crater in Arizona, myself included, have used this fact, and the circumstance that the material is abundantly stained with nickel-iron oxide, as a conclusive argument—for such it is—in favor of the impact theory rather than the volcanic theory of origin. I am assured by Dr. Merrill and others that there is no record of a sudden outburst of volcanic action wherein the heat generated was sufficient to fuse crystalline quartz. The only case of quartz being fused by a sudden rise in temperature to the necessary degree of heat to effect a result comparable to that produced here is that of the more or less familiar action of the lightning striking sandstone or sand and altering it to what is known as fulgurite glass. No volcanic action, however violent or however long con-

[1] *Proc. U. S. National Museum*, Vol. XXXII, pp. 547–550, June 15, 1907, and *Smithsonian Misc. Collections* (Quarterly Issue), Vol. 50, Part 4, pp. 461–498, pls. 61–75, January 27, 1908. See also the description of this metamorphosed sandstone in my National Academy paper.

tinued, has been known to produce such an effect. The only comparison which occurs to me and which will at all fit the facts is that of the striking of a heavy armor-piercing projectile upon armor plate. There, I understand, a very high heat is generated momentarily, as was certainly the case at the Arizona crater. There also the heat of impact is sufficient to not only fuse a small portion of the target, but a small portion of the projectile, since momentarily iron-and-nickel vapor is produced. That this vapor of iron and nickel was also produced at the crater, being derived from the impacting body, is evidenced by the fact that this particular variety of fused sandstone, referred to by me as "Variety B" of metamorphosed sandstone in my National Academy paper, is nearly always more or less abundantly stained by iron and nickel oxide. The fact that this stain is often found in places where the metamorphosed sandstone has gaped open under the influence of intense heat and then closed again upon cooling, is most significant.

Now it must not be forgotten that the white or gray saccharoidal sandstone, small portions of which have been fused in this way, does not outcrop anywhere nearer than the Grand Canyon of the Colorado, seventy miles distant, where it is known as the White Wall or Cross-bedded sandstone and overlies, as at Meteor Crater, the Red Wall or Red Beds sandstone. At the crater the upper portion of this sandstone occupies a position about 350 feet below the surface of the plain, being overlaid by about 300 feet of the Aubrey limestone and 40 or 50 feet of the purplish-red sandstone, which, in the form of small buttes, is found all over the surrounding otherwise almost level plain. It must be remembered also that all the strata in this locality are horizontal. Clearly, nickeliferous iron had penetrated into and, as we now have strong reason to believe, through this bed of white or gray sandstone, and we know that nothing terrestrial in this vicinity contains nickel in any form. The only possible source of this stain is, therefore, the meteoric iron, the occurrence of which has been very fully described in my previous papers. (See Plate XXIII, showing the distribution of meteoric iron around the crater.) It seems to me, therefore, that this peculiar vesicular form of metamorphosed sandstone, which was certainly produced by sudden and intense heat and which is so abundantly stained with nickel and iron oxide, in itself furnishes an incontrovertible proof of the impact theory of origin, the opinion of certain members of the United States Geological Survey to the contrary notwithstanding.

Professor Elihu Thomson has given me permission to quote a statement which he made to me in a letter written a few days after he visited the crater some years ago, as follows: "This Arizona crater bears all the evidences of impact and the evidences of nothing else." This is the complete story told in a few words. It will be in the interest of science if scientific men, and especially those of the United States Geological Survey who deny this theory of origin, will present their reasons for maintaining the hypothesis that the crater was due to some manifestation of volcanic activity. I believe that it will be easy to refute any argument they may advance. No examination of the crater since the exploratory work was done has been made by any members of the Survey, to the best of my knowledge and belief. Therefore, unless they can satisfactorily account for the facts which I have stated in this and in my previous papers on the subject on some other theory than that of impact by a great mass of meteoric iron, it would seem that I can fairly claim to have proved the theory that the crater was formed by this agency.

There is good reason to believe that the meteoric mass was a dense cluster of iron meteorites and possibly was the head of a small comet which was not moving at very high speed, astronomically considered, since there is no evidence, beyond the very slight evidence referred to above, of the volatilization of any portion of the mass. Moreover, it is certain that the siliceous limestone bed, which it encountered after passing through the 40 to 50 feet of overlying purplish-red sandstone, would have been readily fused had the impact been such as we can reasonably suppose it to have been had there been a head-on collision between this small cluster of iron meteorites or cometary body and the earth. Besides this, as anyone who knows anything about ballistics will at once acknowledge, there would have been no such penetration as we now know took place: nearly, if not fully, 1,200 feet into solid limestone and sandstone strata. It has been inferred, therefore, that the cluster of iron meteorites may have followed after the earth and that the blow delivered was not such as it would have been if there had been a direct head-on collision. We now know that the mass, probably weighing as much as 10,000,000 tons, if not more, penetrated through the white or gray sandstone and as far down as the top of the Red Beds sandstone (Red Wall sandstone of the Grand Canyon section). Several cores from this sandstone bed, showing it to be undisturbed and lying in a horizontal position, have been brought up by the drill directly under the centre of the floor of the crater and at a

depth of from 900 feet to over 1,000 feet below the floor of the crater. They are to be seen at the American Museum of Natural History, New York.

Only a small and unfortunately the central portion of the crater has been explored by the drill, not more than $\frac{1}{19}$ of the total area of the crater, but undoubted meteoric material (small pieces of "iron shale" or magnetic nickel-iron oxide) have been brought up by the drill, as stated in my previous papers, from a depth of between 700 and 800 feet below the level of the floor of the crater, which is about 440 feet, on an average, below the level of the surrounding plain. The drill holes were located there because we did not at the time this drilling was done appreciate the direction from which the meteoric mass approached or properly interpret the evidence which now causes us to believe that it lies under the southern wall of the crater, some *2,000 feet* distant from where the drilling was done. We did not take into consideration certain facts now very plain to us and to anyone who may visit the crater or carefully study the maps, once his attention is called to these facts, which should have shown us that it approached at quite an angle from the north, perhaps as much as 30° from the vertical.

In the first place, the greatest amount of iron meteorites and especially those of the "shale ball" variety, described in my previous papers, have been found on the northern slope of the crater and on the plain beyond—accurately, slightly to the east of a north and south line passing through the centre of the crater. In this connection it may be of some interest to know that there was found about a mile and a half from the crater in a north-northeast direction three years ago the largest Canyon Diablo iron meteorite which has ever been found. The following are the dimensions of this meteorite, which is of the ordinary Canyon Diablo type, with characteristic pittings, etc.:

Length	3′ 2″
Width	2′ 5″
Height	1′ 3½″
Greatest circumference	8′ 3½″
Least circumference	5′ 7″
Estimated weight	Between 1,700 and 2,000 pounds.

It is to be seen at the museum[2] which has been built at the crater.

[2] The collection of meteorites, metamorphosed sandstone, specimens of all the strata penetrated, etc., in this museum and in the collection at the American Museum of Natural History, in New York City, which has been loaned to it by Princeton University, should be seen by all those who are interested in the subject.

Secondly, vastly more of the fragmentary material, including that which came from its greatest depths, which has been expelled from the crater by the force of the impact, lies on the southern rim than anywhere else.

Other proofs that the meteoric mass which produced the crater by its impact with the earth approached from this direction are that in the south wall of the crater, composed of great limestone and sandstone cliffs, the fact is clearly discernible that this sandstone and limestone have been lifted vertically some 105 feet out of position for a total length of nearly one-half mile. On either side of this great uplift the formations are tilted violently backward, a fault separating them from the central uplifted mass (see Plates XXI and XXII). Moreover, a distinct bending or arch can be seen in the lines of stratification of the rocks composing this central mass which has been vertically uplifted and which probably weighs in the neighborhood of 50,000,000 tons. The highest point of this curvature is in the exact centre or midway between the point where the strata have been turned backward, as described. This would seem to indicate that something was wedged or intruded underneath this great mass of rock and lifted it vertically upward. The central portion of this mass of rock so uplifted is almost due south of the centre of the crater or nearly opposite to that portion of the crater's rim and the plain beyond on which the greatest number of ordinary Canyon Diablo meteorites and the so-called "shale ball" meteorites have been found. Also beginning at the north the strata exposed in the circular wall of the crater increase in the dip representing their backward tilting on each side of the crater right around to the faults which mark the east and west sides of this uplifted mass (see Plates XXI and XXII). When these facts are considered in connection with that of the great fragmentary masses of limestone being collected together in what I have heretofore referred to as "fields of limestone boulders," which lie to the east and west of a north and south line passing through the crater, conviction is forced upon the mind that the mass which made the crater, and which according to our present knowledge of physics and chemistry must lie somewhere in its depths, approached the earth from a northerly direction and held to its course as a rifle bullet would until perhaps it came to the top of the hard Red Beds sandstone stratum, when possibly it may have been deflected somewhat. Apparently, however, it advanced sufficiently far underneath the white or gray sandstone and the overlying limestone to uplift the portion of the

wall of the crater referred to above more than 100 feet out of its proper position. What could be more natural under these conditions than that we would have found nothing in the centre of the crater except some little pieces of iron oxide representing largely sparks or bits of metal which were literally torn off the projectile as it advanced through the rock target? By far the greater portion of it must have held together, as a charge of shot holds together for a short distance after it leaves the muzzle of a shotgun. It is considered extremely likely that the major portion of the mass lies under the southern wall of the crater and particularly under that portion of it which has been uplifted in the manner that I have attempted to describe.

The theory has been advanced that this great crater was partially formed by the heating of the water in the moist sandstone converting it almost instantly into steam. I have no doubt that this action contributed in a measure to excavate the crater, but I do not think that it contributed very largely to the general effect. It seems to me that it is hardly necessary to call in any other agency to account for the observed facts than the excavating effect of such a projectile. In short I believe the crater would have been practically as large as it is to-day if there had been no water in the sandstone. We well know from repeated borings by the Atchison, Topeka & Santa Fe R. R. Company that these strata contain very little water to-day and all the evidence is in favor of the crater's being of recent origin, the Indians of that section having a legend connected with the fall.

Having once been convinced of the correctness of the impact theory of origin, the size of the meteoric mass which formed the projectile becomes of interest. It is hardly conceivable that its weight was less than five million tons. It may have been 10,000,000 tons, or twice that weight. Admitting that it was a cluster that produced the result, the wonder is that it was as small as we now realize it must have been. These masses of meteoric material we know to be flying through space in the vicinity of our solar system. They possibly represent the small remaining portions of the nebula out of which our system was made. Most of them have probably long since been gathered into the sun or into some of the planetary bodies. Saturn's rings, I believe, are largely composed of meteorites. They probably present an early stage of moon-making. The craters on the moon's surface are much more thinkable in size than the Arizona crater. Most of the craters on the moon's surface, which I firmly believe to

be impact craters, are vastly larger than our Arizona crater, and one of them is even 150 miles in diameter. When one who is familiar with the Arizona crater examines the lunar craters through a good telescope they are at once seen to show the main features of the former. The relation of width to depth is the same. Most of the ejected material lies close around the lunar craters and forms the so-called rim, as in the case of the Arizona crater. There are spurts or tongues of ejected material in the Arizona crater and presumably in the lunar craters. Even the peculiar conical central hill or mountain which is observed in most of them and which I confidently assert cannot be explained on any theory of volcanic action, has its counterpart in our own Silica Hill at Meteor Crater (see Plates XXI and XXII). It probably exists in all of the lunar craters, but in the very small ones it is not easily discernible on account of the smallness of the crater and because, as in our crater, the effect has been somewhat masked. This hill in the Arizona crater is now somewhat masked by the overlying lacustrine sediments and by fine material deposited by the action of wind over it. For a long time its origin puzzled us greatly. It now seems to have been a necessary feature of the impact. These central conical hills or veritable mountains in the larger lunar craters would seem to be due to the same physical law which we see in operation when we drop a stone into water or soft mud, with which solid rock can be compared if the projectile strikes it at sufficient speed. A raindrop falling on still water produces for a moment the same small conical-shape in the centre of the cavity caused by the impact. In the case of water, of course, it soon mingles with the surrounding water; in the case of rock fragments or rather stiff mud it remains. In this connection one should read *A Study of Splashes*, by Professor W. A. Worthington, of Devonport, England, in which the author has introduced some quite wonderful photographs and arrived at certain conclusions with regard to the behavior and flow of solid substances under great pressure, suddenly applied, being analogous to the motion set up in liquids or viscous material upon impact. These conclusions seem to be fully warranted and also seem to go far toward explaining the presence of the conical-shaped hills in nearly all of the lunar craters. Anyone who will make a careful study of our Arizona crater and will then read Worthington's book, studying the diagrams he has made, and will then turn his attention to the lunar craters, cannot escape the conviction that the lunar craters are impact craters. Why the moon should have been so abundantly bom-

barded and the earth so seldom bombarded during recent geological history is seemingly difficult to explain, but one must not forget that the moon has been without an atmosphere for perhaps a great many million years and all the bombardment to which it has been subjected during this vast period of time is clearly and permanently recorded.

May it not be possible that when one holds in his hands one of the meteorites that occasionally reach this earth and which reached it on its present surface in far greater numbers at and around Meteor Crater in Arizona than any other locality known to us, he is holding in his hands something older than our sun or any of the planets which revolve about it; in fact, that he is holding in his hands something which has literally formed part of the nebula out of which our whole solar system has been built up? If this be in accordance with the facts it would help to confirm the more recent theories of the building up of the planetary systems as put forward by Chamberlin and Moulton.

It seems to me to be not inappropriate to bring this paper to a close by quoting in substance an argument which I recently heard used by Dean W. F. Magie, Professor of Physics at Princeton University, in favor of the impact theory of origin of the Arizona crater and as against the steam explosion theory of origin, which has been advanced and persisted in notwithstanding all the evidence presented in the many papers which have been written on the subject since the publication of my first paper read before The Academy of Natural Sciences of Philadelphia. Dean Magie spent a fortnight at Meteor Crater several years ago studying the various phenomena in connection with the crater and carefully checking the statements of fact made by me in the National Academy paper above referred to. The argument is as follows:

First, on the doctrine of probabilities, the chances are one in many millions that the greatest known shower of iron meteorites should have fallen on the exact spot, with the Arizona crater as the centre of its distribution (by consulting Plate XXIII it will be noticed that the meteorites increase in number as one approaches the crater), at which a single, unprecedented steam explosion on a rapidly revolving earth occurred.

Secondly, that the chances are one in many more millions that this shower should have fallen on the exact site chosen for such an unprecedented steam explosion at the same instant of time that the steam explosion occurred.

Thirdly, that the chances are again one in millions that the steam

explosion should have produced not only such a peculiarly symmetrical crater as has been described in the various papers which have been recently written concerning it, but should have produced one which furnishes so much other evidence strongly confirming the theory of impact as against the theory of steam explosion.

Consequently, it is perfectly fair mathematically to multiply these three and for one to say, on the theory of probabilities, that the chances are one in the product of all these millions that the crater was formed by a steam explosion. This of course is negligible.

Explanation of Plates XXI–XXIII.

Plate XXI.—Map of Meteor Crater, Arizona (six miles south of Sunshine Station, Atchison, Topeka & Santa Fe R. R., Coconino County, and in Sections 13 and 24, T. 19, N. R., 12½ E.).

Plate XXII.—Rough sketch map showing distribution of major portion of fragmentary material ejected from Meteor Crater, Arizona.

Some rock fragments have been thrown as far as two miles from the crater. This map merely shows manner of distribution and relative quantity of material near the crater. Very much more material has been thrown to the south (generally speaking) than elsewhere, *i.e.*, the mass of rock fragments is much thicker there than elsewhere and the rock has been more finely crushed. The rock fragments seem to have been thrown furthest to the northeast by east, where they thinly cover a large area.

Legend.—

Crater Rim.

Lower limit of *bulk* of ejected material which forms to a large extent the so-called mountain. This line necessarily approximate.

Limestone fragments, the most coherent rock thrown out of the crater.

Fields of big limestone boulders on the east and west slopes of the mountain.

White or gray saccharoidal sandstone fragments. These frequently show cross bedding.

Brown sandstone fragments and brown sand due to their disintegration. Much of this sand has been drifted to the eastward by the prevailing winds.

Thin sheets or individual masses of ejected limestone far out on the plain. These scattered fragments are found 1½ miles from the crater rim to northeast, 1¾ to 2 miles east and about 1 mile southeast. Map too small to show their distribution except in a general way.

Plate XXIII.—Map showing distribution of meteoric material around Meteor Crater, Coconino County, Arizona.

Legend.—

Meteoric irons (ordinary Canyon Diablo siderites) from 10 pounds to 547 pounds, discovered by Standard Iron Company.

Meteoric irons, from 10 pounds to 1000 pounds, discovered by Mexicans employed by F. A. Volz *et al.* previous to acquisition of property by S. I. Co.

\+ Meteoric irons. Small. Discovered by S. I. Co. Thousands of the small irons found. Hence distribution only approximated. (These are generally only a few grains or ounces in weight, irons weighing from 1 to 10 pounds found only occasionally.)

◈ Large irregular masses of meteoric iron oxide or large "shale balls," from 100 pounds to 300 pounds in weight, due to oxidation of meteoric iron rich in chlorine and sulphur, or shale-ball iron.

c Small broken fragments of meteoric iron oxide or "iron shale" (a few grains or ounces, rarely a pound in weight). Thousands of such pieces found, hence distribution only approximated.